

Influence of Damped Propagation of Dopant on the Static Linear and Nonlinear Polarizabilities of Quantum Dot

Suvajit Pal^{*1}, Manas Ghosh²

^{*1}Department of Chemistry, Hetampur Raj High School, Hetampur, Birbhum 731124, West Bengal, India.

²Department of Chemistry, Physical Chemistry Section, Visva Bharati University, Santiniketan, Birbhum 731 235, West Bengal, India.

^{*1}suvajitchem@gmail.com; ²pcmg77@rediffmail.com

Abstract

We investigate the profiles of diagonal components of static linear (α_{xx} and α_{yy}), and first nonlinear (β_{xxx} and β_{yyy}), optical responses of repulsive impurity doped quantum dots. The dopant impurity potential assumes Gaussian form. The dopant is considered to be propagating under damped condition which is otherwise linear inherently. The study principally puts emphasis on investigating the role of damping strength on the static polarizability components. In view of this the doped dot is exposed to a static electric field of given intensity. The damping strength interplays with the confinement potentials and fabricate the polarizability components delicately through the emergence of maximization, minimization, and saturation. Also, the difference in the extent of inherent confinement in x and y -directions has been found to modulate the polarizability components.

Keywords

Quantum dot; Impurity; Static Polarizability; Damping; Dopant Propagation; Confinement Potential

Introduction

Modern nanotechnology is advancing towards manufacture of new high-performance devices having significant technological applications. In view of this the linear and nonlinear optical properties of devices are found to be quite relevant. Low-dimensional quantum systems are well-known for exhibiting more prominent nonlinear optical effects than the bulk materials, and possess broad applications in high-speed electro-optical modulators, far infrared photo-detectors, semiconductor optical amplifiers and so on. Moreover, a lot of important information about the energy spectrum, the Fermi surface of electrons, and the value of electronic effective mass of these systems can be gathered on investigating their optical properties. In this context quantum dot (QD) has proved itself as a high performance semiconductor optoelectronic device. However, the properties of QD are strongly affected by the presence of impurities because of subtle interplay operating between QD confinement sources and impurity potentials. As a natural consequence we find a seemingly large number of important investigations in this field (Aichinger et al., 2006; Baskoutas et al., 2004; Gülveren et al., 2005; Movilla and Planelles, 2005; Räsänen et al., 2004; Tas and Sahin, 2012). In practice, although the current technology is quite capable of manufacturing high purity QDs, the possibility of impurity contamination still persists. Particularly, during the fabrication of QD on the basis of colloidal solution, the impurity can infest the QD surface.

The impurity potential modifies the dot confinement and thus engineers the electronic structure of these materials. In fact such modification can be achieved by tailoring the shape and size of the doped QD. The tailoring eventually changes the spatial disposition of energy levels and produces desirable optical transitions. Moreover, relevant to the optical transitions of QDs, the interplay between the dot confinement and impurity potential enhances the oscillator strength of electron-impurity excitation. Added to this, the optical transition energy depends on the confinement strength (i.e. the quantum size) and makes the resonance frequency more adjustable. These features are obvious for the manufacture of optoelectronic devices with controllable emission and transmission properties and ultra-narrow spectral linewidths. In consequence, impurity driven modulation of linear and nonlinear optical

properties assumes importance because of practical applications in photodetectors and high-speed electro-optical devices (Vahdani and Rezaei, 2009; Xie^a, 2010). The fascinating optical properties of doped QDs have made them useful materials for various optoelectronic applications resulting in many important works on both linear and nonlinear optical properties of these structures (Çakir et al., 2010; Chen et al., 2013; Duque et al., 2013; Karabulut and Baskoutas, 2008; Khordad, 2010; Kumar et al., 2012; Sadeghi and Avazpour, 2011; Sahin, 2009; Vahdani and Rezaei, 2009; Yakar et al., 2010).

The application of electric field provides pertinent information about the confined impurities (López et al., 2008; Zeng et al., 2012). The electric field causes polarization of the carrier distribution with a consequent energy shift of the quantum states. The changed energy spectrum of the carrier could be harnessed to control and modulate the intensity output of optoelectronic devices. Furthermore, the electric field could destroy the symmetry of the system thereby leading to emergence of nonlinear optical properties. Among the nonlinear optical properties the second-order quantity is simplest and produces lowest-order nonlinear effect with magnitude usually stronger than higher-order ones, particularly if the quantum system demonstrates significant asymmetry. Thus, the applied electric field turns out to be extremely important so far as optical properties of doped QDs are concerned (Baskoutas et al., 2007; Duque et al., 2001; Karabulut and Baskoutas, 2008; Karabulut and Baskoutas, 2009; Lien and Trinh, 2001; Li and Xia, 2007; Murillo and Porras-Montenegro, 2000; Narayanan and Peter, 2012; Peter, 2006; Rezaei et al., 2011; Sadeghi, 2011; Vahdani and Rezaei, 2009; Xie and Xie, 2009; Xie^a, 2010; Xie^b, 2010; Zheng et al., 2012).

The phenomenon of damping in QD bears a lot of importance in view of fundamental physics as well as nanoelectronic applications. The manufacture of high quality single electron transistors (Guo et al., 1997), logic elements (quantum bits) (Itakura and Tokura, 2003), memory cells (Yano et al., 1999), and lasers based on QD heterostructures (Dutta and Strosio, 2000) is very much linked with damping. The phenomenon gains more importance since nanoelectronic devices are often introduced into large integral circuits consisting of densely packed structural elements (Fedorov et al., 2005). The typical length between the elements of integral circuits generally falls within the range of several tens of nanometers. These nanoelectronic devices mutually affect one another and are also influenced by the metallic and doped semiconductor fragments of the heterostructures and integrated circuits. It has also been observed that impurities are very much connected with damping (Li and Arakawa, 1997; Schroeter et al., 1996; Sersel, 1995) and different elementary excitation localized inside QD interplay with damping (Fedorov et al., 2005). The QD carriers have been found to be conspicuously interacting with environmental excitation in the vicinity of dopants. Consequently, we find a good number of studies on the QD electronic damping dynamics initiated by interference from environmental excitation (Itakura and Tokura, 2003). There are also some experimental studies that examine damping in doped quantum confined structures by optical techniques (Ascazubi et al., 2002).

In the present manuscript we have investigated the role of *damping* on the *static* linear and nonlinear polarizabilities of doped QD (Datta and Ghosh, 2011). The static optical response properties of these systems can be important in order to design devices with significant technological applications and can be principally useful in the area of all-optical signal processing. In the present work, for simplicity, we have considered inherently linear propagation of dopant from a fixed dot confinement center which is eventually impeded owing to damping. The damped propagation of dopant annihilates the inversion symmetry of the dot leading to the emergence of non-zero β value. The appropriate time-dependent modulation of spatial stretch of impurity (γ^{-1}) accompanying the damped movement has also been considered in this regard (Pal and Ghosh, 2013; Pal et al., 2013). The diagonal components of linear (α) and first nonlinear (β) polarizabilities have been computed by exposing the QD to an external static electric field. The present investigation principally addresses the role of damping strength (ς) on the profiles of the direct components of linear (α_{xx} , α_{yy}) and first nonlinear (β_{xxx} , β_{yyy}) polarizability and reveals some important aspects.

Method

The model considers an electron subject to a harmonic confinement potential $V(x, y)$ and a perpendicular magnetic field B . The confinement potential reads $V(x, y) = \frac{1}{2}m^*\omega_0^2(x^2 + y^2)$, where ω_0 is the harmonic confinement frequency. Under the effective mass approximation, the Hamiltonian of the system becomes

$$H'_0 = \frac{1}{2m^*} [-i\hbar \nabla + \frac{e}{c} A]^2 + \frac{1}{2} m^* \omega_0^2 (x^2 + y^2). \quad (1)$$

m^* is the effective electronic mass within the lattice of the material considered. We have taken $m^* = 0.067m_0$ and set $\hbar = e = m_0 = a_0 = 1$. This value of m^* closely resembles *GaAs* quantum dots. In Landau gauge [$A = (By, 0, 0)$] (A being the vector potential), the Hamiltonian reads

$$H'_0 = -\frac{\hbar^2}{2m^*} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) + \frac{1}{2} m^* \omega_0^2 x^2 + \frac{1}{2} m^* (\omega_0^2 + \omega_c^2) y^2 - i \hbar \omega_c y \frac{\partial}{\partial x} \quad (2)$$

$\omega_c = \frac{eB}{m^*c}$ being the cyclotron frequency (equivalent to magnetic confinement offered by B). The magnetic field in atomic unit corresponds to field strength of milliTesla (mT) order. We may define $\Omega^2 = \omega_0^2 + \omega_c^2$ as the effective frequency in the y -direction. The model Hamiltonian [cf. eqn (2)] represents a 2-d quantum dot with a single carrier electron (Chakraborty, 1999) with lateral confinement (parabolic) of the electrons in the x - y plane. The parabolic confinement potential often serves as an appropriate representative of the potential in semiconductor structures (Baskoutas et al., 2004; Gülveren et al., 2005; Lien and Trinh, 2001; Murillo and Porras-Montenegro, 2000; Peter, 2006; Sadeghi and Avazpour, 2011; Yakar et al., 2010) and has been actually invoked in the study of optical properties of doped QDs (Çakir et al., 2010). The parabolic potential particularly becomes meaningful when the QDs are fabricated by etching process on a quantum well, by ion implantation or by application of electrostatic gates.

In the present problem we have considered that the QD is doped with a repulsive Gaussian impurity (Halonen et al., 1996; Halonen et al., 1996). Incorporating the impurity potential to the Hamiltonian [cf. eqn (2)] we obtain

$$H_0(x, y, \omega_c, \omega) = H'_0(x, y, \omega_c, \omega) + V_{imp}(x_0, y_0) \quad (3)$$

Where $V_{imp}(x_0, y_0) = V_{imp}(0) = V_0 e^{-\gamma_0[(x-x_0)^2 + (y-y_0)^2]}$ with $\gamma_0 > 0$ and $V_0 > 0$ for repulsive impurity, and (x_0, y_0) denotes the coordinate of the impurity center. V_0 is a measure of the strength of impurity potential whereas γ_0^{-1} stands for the spatial stretch of the impurity potential. The presence of repulsive scatterer represents dopant with excess electrons. The use of such Gaussian impurity potential is quite frequent (Adamowski et al., 2005; Bednarek et al., 2003; Szafran et al., 2001). At this point it needs to be mentioned that Gharaati et al. (Gharaati and Khordad, 2010) introduced a new confinement potential for the spherical QD's called *Modified Gaussian Potential (MGP)* and revealed its effectiveness in determining the spectral energy and wave functions of a spherical quantum dot.

Thus, the problem boils down to modeling the energy eigenvalues and eigenvectors of the two dimensional Hamiltonian H_0 :

$$H_0 \psi_n(x, y) = E_n \psi_n(x, y) \quad (4)$$

Equation (4) turns out to be the energy eigenvalues equation of a two dimensional harmonic oscillator as ω_c (i.e. B) $\rightarrow 0$ and $V_0 \rightarrow 0$. Naturally, we seek diagonalization of H_0 in the direct product basis of harmonic oscillator eigenfunctions. The time-independent Schrödinger equation has been solved using variational method expressing the trial wave function $\psi(x, y)$ in the product basis of harmonic oscillator eigenfunctions (Datta and Ghosh, 2011; Pal and Ghosh, 2013; Pal et al., 2013) $\phi_n(\alpha x)$ and $\phi_m(\beta y)$ respectively, as

$$\psi(x, y) = \sum_{n,m} C_{n,m} \phi_n(\alpha x) \phi_m(\beta y) \quad (5)$$

Where $C_{n,m}$ are the variational parameters and $\alpha = \sqrt{\frac{m^* \omega_0}{\hbar}}$ and $\beta = \sqrt{\frac{m^* \Omega}{\hbar}}$. The general expression for the matrix elements of H'_0 and $V_{imp}(0)$ in the chosen basis are as follows (Datta and Ghosh, 2011; Pal and Ghosh, 2013; Pal et al., 2013):

$$(H'_0)_{n,m;n',m'} = \hbar \left\{ \left(n' + \frac{1}{2} \right) \omega_0 + \left(m' + \frac{1}{2} \right) \sqrt{\omega_0^2 + \omega_c^2} \right\} \delta_{n,n'} \delta_{m,m'}$$

$$-i\hbar\omega_c \frac{\alpha}{\beta} \left[\left\{ \sqrt{\frac{n'}{2}} \delta_{n'-1,n} - \sqrt{\frac{n'+1}{2}} \delta_{n'+1,n} \right\} \left\{ \sqrt{\frac{m'+1}{2}} \delta_{m'+1,m} + \sqrt{\frac{m'}{2}} \delta_{m'-1,m} \right\} \right]. \quad (6)$$

And

$$\begin{aligned} \{V_{imp}(0)\}_{n,m;n',m'} &= \\ V_0 \langle \phi_n(\alpha x) \phi_m(\beta y) | e^{-\gamma_0[(x-x_0)^2 + (y-y_0)^2]} | \phi_{n'}(\alpha x) \phi_{m'}(\beta y) \rangle \\ &= V_0 \langle \phi_n(\alpha x) | e^{-\gamma_0[(x-x_0)^2]} | \phi_{n'}(\alpha x) \rangle \\ &\quad \langle \phi_m(\beta y) | e^{-\gamma_0[(y-y_0)^2]} | \phi_{m'}(\beta y) \rangle \\ &= V_0 D_1 D_2 \sum_{k=0}^{\min(n,n')} \sum_{l=0}^{\min(m,m')} f(k, n, n') g(l, m, m'), \end{aligned} \quad (7)$$

Where,

$$\begin{aligned} f(k, n, n') &= \\ 2^k k! \frac{n}{k} C_k^{n'} C_k^n (1 - \alpha^{*2})^{\frac{n+n'}{2} - k} H_{n+n'-2k}(\alpha_1 \rho_1), \end{aligned}$$

And

$$g(l, m, m') = 2^l l! \frac{m}{l} C_l^{m'} C_l^m (1 - \beta^{*2})^{\frac{m+m'}{2} - l} H_{m+m'-2l}(\beta_1 \rho_2)$$

$H_n(x)$ Stands for the Hermite polynomials of n^{th} order. The various other terms read as follows:

$$\begin{aligned} D_1 &= \frac{A \lambda_1 \pi^{\frac{1}{2}}}{\delta_1}, D_2 = \frac{B \lambda_2 \pi^{\frac{1}{2}}}{\delta_2}, \text{ with } A = \frac{\alpha}{(2^{n+n'} n! n'! \pi)^{\frac{1}{2}}}, \\ B &= \frac{\beta}{(2^{m+m'} m! m'! \pi)^{\frac{1}{2}}}, \delta_1^2 = \alpha^2 + \gamma_0, \delta_2^2 = \beta^2 + \gamma_0, \\ \lambda_1 &= \exp\left[-\frac{\gamma_0 x_0^2 (\delta_1^2 - \gamma_0)}{\delta_1^2}\right], \lambda_2 = \exp\left[-\frac{\gamma_0 y_0^2 (\delta_2^2 - \gamma_0)}{\delta_2^2}\right], \\ \rho_1 &= \frac{\gamma_0 x_0}{\delta_1}, \rho_2 = \frac{\gamma_0 y_0}{\delta_2}, \alpha^* = \frac{\alpha}{\delta_1}, \beta^* = \frac{\beta}{\delta_2}, \alpha_1 = \frac{\alpha^*}{(1 - \alpha^{*2})^{1/2}}, \text{ and } \beta_1 = \frac{\beta^*}{(1 - \beta^{*2})^{1/2}}. \end{aligned}$$

In the linear variational calculation, a considerably large number of basis functions have been exploited after making the routine convergence test.

The dopant propagation can be realized in terms of time-dependent dopant coordinates $x_0 \rightarrow x_0(t)$ and $y_0 \rightarrow y_0(t)$. Such a dopant propagation, in turn, makes γ (the spatial spread of dopant) time-dependent (Pal and Ghosh, 2013; Pal et al., 2013) as the latter depends on the instantaneous dopant location and therefore reads as $\gamma(t) = \gamma_0 \exp\{-\eta \sqrt{x_0^2(t) + y_0^2(t)}\}$, where η is a very small parameter and γ_0 is the initial value of γ . The time-dependence thus indicates a lazy extension of the domain over which the influence of dopant is dispersed that ensues its drift. Now the time-dependent Hamiltonian reads

$$H(t) = [H_0 - V_{imp}(0)] + V_1(t), \quad (8)$$

Where

$$V_1(t) = V_0 e^{-\gamma(t)[(x-x_0(t))^2 + (y-y_0(t))^2]} \quad (9)$$

In the present work the intrinsic time-dependence of dopant propagation has been considered to be linear for convenient handling of the problem so that $x_0(t) = x_0 + at$, $y_0(t) = y_0 + bt$ (Pal and Ghosh, 2013; Pal et al., 2013). The hindrance offered by damping to the dopant propagation has been modeled by introducing an exponentially decaying term phenomenologically through the parameter ζ (a measure of damping strength) giving rise to $x_0(t) = (x_0 + at)e^{-\zeta t}$ and $y_0(t) = (y_0 + bt)e^{-\zeta t}$. Such representation causes a faster fall of dopant propagation with increase in the

damping strength in comparison with the undamped motion. The spatial stretch of impurity (γ^{-1}) also changes accordingly. The matrix element involving any two arbitrary eigenstates p and q of H_0 due to $V_1(t)$ reads [for the expressions of various related terms see (Pal and Ghosh, 2013; Pal et al., 2013)].

$$\begin{aligned} V_{p,q}^{imp}(t) &= \left\langle \psi_p(x, y) \left| V_1(t) \right| \psi_q(x, y) \right\rangle \\ &= \sum_{nm} \sum_{n'm'} C_{nm,p}^* C_{n'm',q} \\ &\quad \langle \phi_n(\alpha x) \phi_m(\beta y) | V_1(t) | \phi_{n'}(\alpha x) \phi_{m'}(\beta y) \rangle \\ &= V_0(t) \sum_{j=1}^{16} V_{p,q}^j(t) \end{aligned} \quad (10)$$

The external static electric field V_2 of strength ε is now switched on with

$$V_2 = -\{\varepsilon_x |e|x + \varepsilon_y |e|y\} \quad (11)$$

Where ε_x and ε_y are the field intensities along x and y directions. Now the time-dependent Hamiltonian reads

$$H(t) = [H_0 - V_{imp}(0)] + V_1(t) + V_2. \quad (12)$$

The matrix elements due to V_2 reads

$$\begin{aligned} (V_2)_{n,m;n',m'} &= \left\langle \psi_p(x, y) \left| V_2 \right| \psi_q(x, y) \right\rangle \\ &= \\ &\quad \sum_{nm} \sum_{n'm'} C_{nm,p}^* C_{n'm',q} \\ &\quad \langle \phi_n(\alpha x) \phi_m(\beta y) | V_2 | \phi_{n'}(\alpha x) \phi_{m'}(\beta y) \rangle \\ &= \varepsilon_x \sum_{nm} \sum_{n'm'} C_{nm,p}^* C_{n'm',q} \left[\frac{1}{\alpha} \left\{ \sqrt{\frac{n'+1}{2}} \delta_{n'+1,n} + \sqrt{\frac{n'}{2}} \delta_{n'-1,n} \right\} \delta_{m,m'} \right] \\ &\quad + \varepsilon_y \sum_{nm} \sum_{n'm'} C_{nm,p}^* C_{n'm',q} \left[\frac{1}{\beta} \left\{ \sqrt{\frac{m'+1}{2}} \delta_{m'+1,m} + \sqrt{\frac{m'}{2}} \delta_{m'-1,m} \right\} \delta_{n,n'} \right] \end{aligned}$$

The time-dependent wave function can now be described by a superposition of the eigenstates of H_0 , i.e.

$$\psi(x, y, t) = \sum_q a_q(t) \psi_q \quad (13)$$

and the time-dependent Schrödinger equation (TDSE) [cf. eqn (14)] containing the evolving wave function [cf. eqn(13)] has now been solved numerically by 6-th order Runge-Kutta- Fehlberg method with a time step size $\Delta t = 0.01$ a.u. and numerical stability of the integrator has been verified.

$$i\hbar \frac{\partial \psi}{\partial t} = H \psi$$

Or equivalently

$$i\hbar \dot{a}_q(t) = H a_q(t) \quad (14)$$

The numerical solution of TDSE [cf. eqn (14)] gives the time-dependent superposition coefficients with the initial conditions $a_p(0) = 1$, $a_q(0) = 0$, for all $q \neq p$, where p may be the ground or any other excited states of H_0 . The quantity $P_k(t) = |a_k(t)|^2$ can be used as a measure of population of k^{th} state of H_0 at time t . Actually $P_k(t)$ is the probability of observing the electron in the k^{th} eigenstate and is therefore given by modulus square of the time-dependent superposition coefficients.

The energy of the system E displays typical dynamics when represented as

$$E(t) = \sum_k E_k(0) P_k(t), \quad (15)$$

Where $E_k(0)$ is the energy of k^{th} eigenstate of H_0 at $t = 0$. The time-average energy of the dot $\langle E \rangle$ in the presence of damping and static electric field is computed by numerically integrating the following expression:

$$\langle E \rangle = \frac{1}{T} \int_0^T E(t) dt \quad (16)$$

Where T is the final time up to which the dynamic evolution of the system is monitored. We have determined the values of $\langle E(\pm \varepsilon_x, \varepsilon_y = 0) \rangle$, $\langle E(\pm 2\varepsilon_x, \varepsilon_y = 0) \rangle$, $\langle E(\varepsilon_x = 0, \pm \varepsilon_y) \rangle$, and $\langle E(\varepsilon_x = 0, \pm 2\varepsilon_y) \rangle$ and used the data to compute the direct components of frequency dependent polarizability of the dot by the following relations obtained by numerical differentiation (Datta and Ghosh, 2011):

$$\alpha_{xx} \varepsilon_x^2 = \frac{5}{2} \langle E(0) \rangle - \frac{4}{3} [\langle E(\varepsilon_x) \rangle + \langle E(-\varepsilon_x) \rangle] + \frac{1}{12} [\langle E(2\varepsilon_x) \rangle + \langle E(-2\varepsilon_x) \rangle], \quad (17)$$

And a similar expression for $\alpha_{yy} \varepsilon_y^2$. The diagonal components of first non-linear polarizability (the quadratic hyperpolarizability) are given by components that are calculated from the following expressions.

$$\beta_{xxx} \varepsilon_x^3 = [E(\varepsilon_x, 0) - E(-\varepsilon_x, 0)] - \frac{1}{2} [E(2\varepsilon_x, 0) - E(-2\varepsilon_x, 0)]. \quad (18)$$

And a similar expression is used for β_{yyy} component.

Results and Discussion

Linear Polarizability (α):

In this section we would like to discuss the influence of damping strength (ζ) on the direct components (α_{xx} and α_{yy}) of linear polarizability. Fig. 1 displays the variation of α_{xx} and α_{yy} components with ζ . In the limit of extremely small damping strength ($\zeta \rightarrow 0$) both the components start from a very high value. However, both the components exhibit steep fall with further increase in ζ . At a damping strength of $\zeta \sim 10^{-3}$ a.u. the linear polarizability components undergo saturation with further increase in damping strength. The initial sharp fall of α components with increase in ζ can be due to the fact that an increase in damping strength restricts the motion of dopant away from the dot confinement center. Consequently, the dopant suffers some enhanced confinement which reduces the dispersive nature of the system forcing the α components to diminish. Further increase in ζ impedes the dopant motion so severely that it is compelled to reside very close to the dot confinement origin. The strong dot-impurity repulsive interaction now increases the dispersive character of the system which may lead to an enhancement of α components. The saturation of α components beyond $\zeta \sim 10^{-3}$ a.u. indicates kind of compromise between the reverse factors that govern the dispersive character of the system.

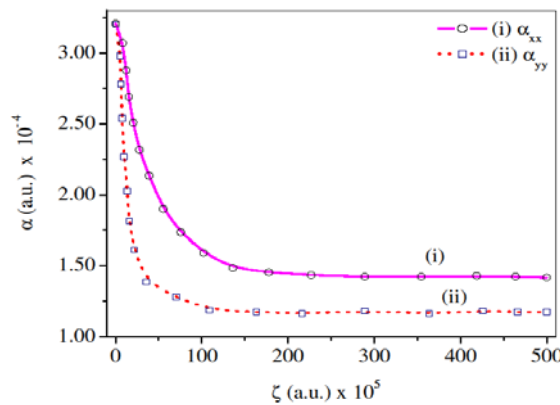


FIG. 1: PLOT OF α COMPONENTS VS. ζ : (I) FOR α_{xx} AND (II) FOR α_{yy} .

It needs to be further noted that the y -direction suffers from inherently greater confinement in comparison with the x -direction [cf. eqn (2)]. As a result the α_{xx} component displays higher magnitude than its y -directional counterpart [fig. 1].

First Nonlinear Polarizability (β):

The following section describes the influence of damping strength on the direct components (β_{xxx} and β_{yyy}) of first nonlinear polarizability. Figs. 2a and 2b reveal the pattern of variation of β_{xxx} and β_{yyy} as a function of ζ . Unlike

linear polarizability, here the components show some noticeable differences in their behaviors as ζ is varied. The inherently strong confinement in the y -direction appears to be the major cause for displaying such a behavior. The β_{xxx} component evinces a minimization at a damping strength of $\zeta \sim 2.0 \times 10^{-4}$ a.u. [fig. 2a] whereas the β_{yyy} maximizes at $\zeta \sim 1.5 \times 10^{-4}$ a.u. [fig. 2b].

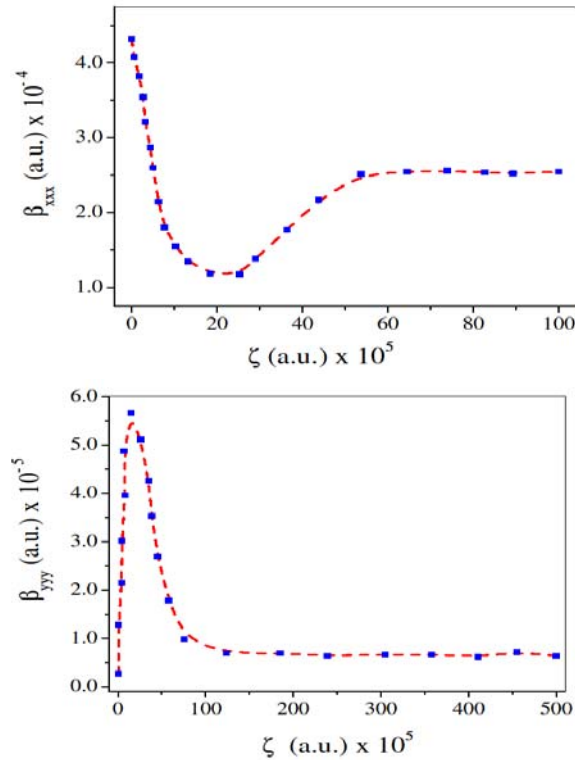


FIG. 2: PLOT OF β COMPONENTS VS. ζ : (A) FOR β_{xxx} AND (B) FOR β_{yyy} .

However, both the components ultimately settle to some steady value in the over damped domain. The observed behavior can be conceived as a resultant effect of damping strength, the confining forces and the dot-impurity repulsive interaction. At low damping strength the dopant remains considerably away from the confinement center because of its drift and feels little repulsive force. A large ζ value makes the drift highly hindered and the dopant remains close to the confinement center. The proximity of the dopant to the confinement center increases the symmetric nature of the system which could cause a huge fall in β_{xxx} component leading to its minimization. On contrary, because of the said proximity the intense dot-impurity repulsive interaction now governs the β_{yyy} component and maximizes it. The severity of the said repulsive interaction is also reflected by the enhanced magnitude of β_{yyy} component ($\sim 10^5$ a.u.) over that of β_{xxx} ($\sim 10^4$ a.u.). Thus, the emergence of maximization for β_{yyy} component indicates dominance of dot-impurity repulsive interaction over that of the confining forces. The saturation in the β components in the over damped regime manifests kind of balance between the several parameters that controls the optical responses.

Conclusions

The diagonal components of static linear and first nonlinear polarizabilities of impurity doped quantum dots have been investigated as the dopant propagates under damped condition. Special focus has been given on the dependence of the polarizability components on the damping strength. In practice, they are found to be dependent on the interplay between damping strength and the strength of the confining potentials. The damping strength basically arrests the motion of the dopant in the vicinity of the dot confinement center. This, however, depending upon the resultant effect of confining force and dot-impurity repulsive interaction, causes sharp fall, maximization, minimization, and saturation in the linear and nonlinear polarizability components. The intrinsically different extents of confinements in x and y -directions mingle with the restricted motion of the dopant because of damping and affect the polarizability. The results are thus quite interesting and expected to bear significance in the relevant

field of research.

ACKNOWLEDGEMENTS

The authors S. P. and M. G. thank D. S. T-F. I. S. T (Govt. of India) and U. G. C.-S.A. P (Govt. of India) for partial financial support.

REFERENCES

- [1] Adamowski J., Kwaśniowski A., and Szafran B. "LO-phonon-induced screening of electron-electron interaction in D⁺ centres and quantum dots". *J. Phys: Cond. Mat.* 17 (2005): 4489-4500.
- [2] Aichinger M., Chin S. A., Krotscheck E., and Räsänen E. "Effects of geometry and impurities on quantum rings in magnetic fields". *Phys. Rev. B* 73 (2006): 195310 (8 pages).
- [3] Ascazubi R., Akin O. C., Zaman T., Kersting R., and Strasser G. "Dephasing in modulation-doped quantum structures probed by THz time-domain spectroscopy". *Appl. Phys. Lett.* 81 (2002): 4344-4346 and references therein.
- [4] Baskoutas S., Paspalakis E., and Terzis A. F. "Electronic structure and nonlinear optical rectification in a quantum dot: effects of impurities and external electric field". *J. Phys: Cond. Mat.* 19 (2007): 395024 (9-pages).
- [5] Baskoutas S., Terzis A. F., and Voutsinas E. "Binding energy of donor states in a quantum dot with parabolic confinement". *J. Comput. Theor. Nanosci.* 1 (2004): 317-321.
- [6] Bednarek S., Szafran B., Lis K., and Adamowski J. "Modeling of electronic properties of electrostatic quantum dots". *Phys. Rev. B* 68 (2003): 155333 (9-pages).
- [7] Çakir B., Yakar Y., Özmen A., Özgür Sezer M., and Sahin M. "Linear and nonlinear optical absorption coefficients and binding energy of a spherical quantum dot". *Superlattices and Microstructures* 47 (2010): 556-566.
- [8] Chakraborty T., *Quantum Dots-A Survey of the Properties of Artificial Atoms*. Amsterdam: Elsevier, 1999.
- [9] Chen T., Xie W., and Liang S. "Optical and electronic properties of a two-dimensional quantum dot with an impurity". *J. Lumin.* 139 (2013): 64-68.
- [10] Datta N. K., and Ghosh M. "Impurity strength and impurity domain modulated frequency-dependent linear and second nonlinear response properties of doped quantum dots". *Physica Status Solidi B* 248 (2011): 1941-1948 and references therein.
- [11] Duque C. A., Montes A., and Morales A. L. "Binding energy and polarizability in *GaAs*-(*Ga*, *Al*) *As* quantum-well wires". *Physica B* 302-303 (2001): 84-87.
- [12] Duque C. A., Mora-Ramos M. E., Kasapoglu E., Ungan F., Yesilgul U., Sakiroglu S., Sari H., and Sökmen I. "Impurity-related linear and nonlinear optical response in quantum-well wires with triangular cross section". *J. Lumin.* 143 (2013): 304-313.
- [13] Dutta M., and Strosio M. A., *Advances in Semiconductor Lasers and Applications to Optoelectronics*. Singapore: World Scientific, 2000.
- [14] Fedorov A. V., Baranov A. V., Rukhlenko I. D., and Goponenko S. V. "Enhanced intraband carrier relaxation in quantum dots due to the effect of plasmon-LO-phonon density of states in doped heterostructures". *Phys. Rev. B* 71 (2005): 195310 (8 pages).
- [15] Gharaati A., and Khordad R. "A new confinement potential in spherical quantum dots: Modified Gaussian potential". *Superlattices and Microstructures* 48 (2010): 276-287.
- [16] Gülveren B., Atav Ü., Sahin M., and Tomak M. "A parabolic quantum dot with N electrons and an impurity". *Physica E* 30 (2005): 143-149.

- [17] Guo L., Leobandung E., and Chou S. "A Silicon Single-Electron Transistor Memory Operating at Room Temperature". *Science* 275 (1997): 649-651.
- [18] Halonen V., Hyvönen P., Pietiläinen P., and Chakraborty T. "Effects of scattering centers on the energy spectrum of a quantum dot". *Phys. Rev. B* 53 (1996): 6971-6974.
- [19] Halonen V., Pietiläinen P., and Chakraborty T. "Optical-absorption spectra of quantum dots and rings with a repulsive scattering centre". *Europhys. Lett.* 33 (1996): 337-382.
- [20] Itakura T., and Tokura Y. "Dephasing due to background charge fluctuations". *Phys. Rev. B* 67 (2003): 195320 (9 pages) and references therein.
- [21] *J. Appl. Phys.* 101 (2007): 093716 (6 pages). Szafran B., Bednarek S., and Adamowski J. "Parity symmetry and energy spectrum of excitons in coupled self-assembled quantum dots". *Phys. Rev. B* 64 (2001): 125301 (10-pages).
- [22] John Peter A. "Polarizabilities of shallow donors in spherical quantum dots with parabolic confinement". *Phys. Lett. A* 355 (2006): 59-62.
- [23] Karabulut I., and Baskoutas S. "Linear and nonlinear optical absorption coefficients and refractive index changes in spherical quantum dots: Effects of impurities, electric field, size, and optical intensity". *J. Appl. Phys.* 103 (2008): 073512 (5 pages).
- [24] Karabulut I., and Baskoutas S. "Second and Third Harmonic Generation Susceptibilities of Spherical Quantum Dots: Effects of Impurities, Electric Field and Size". *J. Comput. Theor. Nanosci.* 6 (2009): 153-156.
- [25] Khordad R. "Diamagnetic susceptibility of hydrogenic donor impurity in a V –groove $GaAs/Ga_{1-x}Al_xAs$ quantum wire". *Eur. Phys. J. B* 78 (2010): 399-404.
- [26] Kumar K. M., Peter A. J., and Lee C. W. "Optical properties of a hydrogenic impurity in a confined $Zn_{1-x}Cd_xSe/ZnSe$ quantum dot". *Superlattices and Microstructures* 51 (2012): 184-193.
- [27] Li X. -Q., and Arakawa Y. "Ultrafast energy relaxation in quantum dots through defect states: A lattice-relaxation approach". *Phys. Rev. B* 56 (1997): 10423-10427.
- [28] Lien N. V., and Trinh N. M. "Electric field effects on the binding energy of hydrogen impurities in quantum dots with parabolic confinements". *J. Phys: Cond. Mater.* 13 (2001): 2563-2571.
- [29] López S. Y., Porras-Montenegro N., Tangarife E., and Duque C. A. "Tilted electric field and hydrostatic pressure effects on donor impurity states in cylindrical GaAs quantum disks". *Physica E* 40 (2008): 1383-1385.
- [30] Movilla J. L., and Planelles J. "O₂-centering of hydrogenic impurities in quantum dots". *Phys. Rev. B* 71 (2005): 075319 (7 pages).
- [31] Murillo G. and Porras-Montenegro N. "Effects of an Electric Field on the Binding Energy of a Donor Impurity in a Spherical GaAs (Ga; Al) As Quantum Dot with Parabolic Confinement. *Phys. Status Solidi B* 220 (2000): 187 - 190.
- [32] Narayanan M., and John Peter A. "Electric field induced exciton binding energy and its nonlinear optical properties in a narrow $InSb/InGa_{1-x}Sb_x$ quantum dot". *Superlattices and Microstructures* 51 (2012): 486-496.
- [33] Pal S., and Ghosh M. "Excitation kinetics of quantum dot induced by damped propagation of dopant: Role of confinement potential and magnetic field". *Chem. Phys.* 423 (2013): 15-19.
- [34] Pal S., Datta N. K., and Ghosh M. "Influence of Damped Propagation of Dopant on the Excitation Kinetics of Doped Quantum Dots". *J. Phys. Chem. C* 117 (2013): 14435-14440.
- [35] Räsänen E., Könenmann J., Puska R. J., Haug M. J., and Nieminen R. M. "Impurity effects in quantum dots: Toward quantitative modeling". *Phys. Rev. B* 70 (2004): 115308 (6 pages).
- [36] Rezaei G., Vahdani M. R. K., and Vaseghi B. "Nonlinear optical properties of a hydrogenic impurity in an ellipsoidal finite potential quantum dot". *Current Appl. Phys.* 11 (2011): 176-181.

- [37] Sadeghi E. "Electric field and impurity effects on optical property of a three-dimensional quantum dot: A combinational potential scheme". *Superlattices and Microstructures* 50 (2011): 331-339.
- [38] Sadeghi E. and Avazpour A. "Binding energy of an off-center donor impurity in ellipsoidal quantum dot with parabolic confinement potential". *Physica B* 406 (2011): 241-244.
- [39] Sahin M. "Third-order nonlinear optical properties of a one- and two-electron spherical quantum dot with and without a hydrogenic impurity". *J. Appl. Phys.* 106 (2009): 063710 (8 pages).
- [40] Schroeter D. F., Griffiths D. F., and Sersel P. C. "Defect-assisted relaxation in quantum dots at low temperature". *Phys. Rev. B* 54 (1996): 1486-1489.
- [41] Sersel P. C. "Multiphonon-assisted tunneling through deep levels: A rapid energy relaxation mechanism in nonideal quantum-dot heterostructures". *Phys. Rev. B* 51 (1995): 14532-14541.
- [42] Shu-Shen Li, and Jian-Bai Xia. "Binding energy of a hydrogenic donor impurity in a rectangular parallelepiped-shaped quantum dot: Quantum confinement and Stark effects".
- [43] Tas H., and Sahin M. "The electronic properties of core/shell/well/shell spherical quantum dot with and without a hydrogenic impurity". *J. Appl. Phys.* 111 (2012): 083702 (8 pages).
- [44] Vahdani M. R. K., and Rezaei G. "Linear and nonlinear optical properties of a hydrogenic donor in lens-shaped quantum dots". *Phys. Lett. A* 373 (2009): 3079-3084.
- [45] Xie W., and Xie Q. "Electric field effects of hydrogenic impurity states in a disc-like quantum dot". *Physica B* 404 (2009): 1625-1628.
- [46] Xie W^a. "Impurity effects on optical property of a spherical quantum dot in the presence of an electric field". *Physica B* 405 (2010): 3436-3440.
- [47] Xie W^b. "Optical properties an o_-center hydrogenic impurity in a spherical quantum dot with Gaussian potential". *Superlattices and Microstructures* 48 (2010): 239-247.
- [48] Yakar Y., Çakir B., and Özmen A. "Calculation of linear and nonlinear optical absorption coefficients of a spherical quantum dot with parabolic potential". *Optics Commun.* 283 (2010): 1795-1800.
- [49] Yano K., Ishii T., Sano T., Mine T., Muri F., Hashimoto T., Koboyashi T., Kure T., and Seki K. "Single-electron memory for giga-to-tera bit storage". *Proc. IEEE.* 87 (1999): 633-651.
- [50] Zeng Z., Garoufalis C. S., and Baskoutas S. "Combination effects of tilted electric and magnetic fields on donor binding energy in *GaAs/AlGaAs* cylindrical quantum dot". *J. Phys. D: Appl. Phys.* 45 (2012): 235102 (9 pages).
- [51] Zeng Z., Garoufalis C. S., Baskoutas S., and Terzis A. F. "Stark effect of donor binding energy in a self-assembled GaAs quantum dot subjected to a tilted electric field". *Phys.Lett. A* 376 (2012): 2712-2716.